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Microwave properties of DyBCO monodomain in the mixed state and comparison with other RE-BCO systems

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Abstract

We report on microwave measurements on DyBa₂Cu₃O_{7- δ} monodomains grown by the top-seeded melt-textured technique. We measured the field increase of the surface resistance $R_s(H)$ in the a-b plane at 48.3 GHz. Measurements were performed at fixed temperatures in the range 70 K - T_c with a static magnetic field $\mu_0 H < 0.8$ T parallel to the c-axis. Low field steep increase of the dissipation, typical signature of the presence of weak links, is absent, thus indicating the single-domain behaviour of the sample under study. The magnetic field dependence of $R_s(H)$ is ascribed to the dissipation caused by vortex motion. The analysis of $X_s(H)$ points to a free-flow regime, thus allowing to obtain the vortex viscosity as a function of temperature. We compare the results with those obtained on RE-BCO systems. In particular, we consider strongly pinned films of YBa₂Cu₃O_{7- δ} with nanometric BaZrO₃ inclusions.

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1. Introduction

The microwave electrodynamic response in High- T_c Superconductors (HTCS) is a precious tool in the investigation of these materials. It provides a great deal of information concerning fundamental physics [1], as well as allowing to address essential issues in view of technological applications [2]. The microwave response determined at zero field has allowed to address many points such as the temperature dependence of the superfluid density [3–5], and the quasi-particles (QP) properties above and below the superconducting transition [4–6]. By applying a static magnetic field $H > H_{c1}$, HTCS are driven in the mixed state where the presence of vortices allows for the disclosure of additional physics [5]. Vortices, which are set in motion by the Lorentz force exerted by microwave currents, dissipate energy through the QP excitations located in and around their cores, in which the order parameter is depressed. Because of the nature of their cores, vortices can be considered as a window of “quasi-normal” state properties accessible below T_c , embedded in the superconducting condensate, and thus useful to probe “normal”-state-related properties, simultaneously with the superconducting gap issues (in particular, its symmetry).

From the point of view of fundamental physics, it is then interesting to investigate the vortex dissipation, dictated by the quasi-particle density of states (DOS) and relaxation time in the vortex cores.

At the same time, from a technological point of view, it is well known [7] that the power handling of HTCS, relevant to microwave devices, is limited by grain-boundaries contribution (dominant at low fields) as well as by vortex motion, the latter being the ultimate, unavoidable limitation. Within this scenario, the investigation of vortex pinning mechanisms is an essential task. Single crystals are ideal

systems for the study of intrinsic properties, while epitaxial films are of interest for applications. On the other hand, monodomains, despite their technological interest, are rarely the subject of microwave studies. Therefore, in this paper we will present the microwave characterization and study of $\text{DyBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (DyBCO) monodomains. A very few studies of DyBCO at microwaves in the mixed state exist [8], while the parent compound $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) is widely studied. It will demonstrate particularly useful a comparison between data taken in DyBCO monodomains, in YBCO single crystals [9] and in YBCO epitaxial thin films with artificially enhanced pinning [10], as prototypical case for intrinsic and extrinsic behaviour, respectively.

2. Experimental technique and data analysis

The main experimental quantity in microwave experiments is the effective surface impedance $Z_s = R_s + iX_s$. In this work, the surface impedance is measured by means of two cylindrical resonators, a silver-coated metal cavity [11] and a dielectric resonator [12], operating in the TE_{011} mode at approximately 48.3 GHz and 47.7 GHz, respectively. The surface perturbation method is used, with the sample under measurement replacing one of the cavity bases. The microwave currents flow parallel to the sample surface (along the $a - b$ planes for the c -axis oriented samples) on circular patterns. A solid/liquid nitrogen cryostat allows to reach temperatures T as low as 60 K, with temperature control within ± 0.005 K. A conventional electromagnet generates magnetic fields $\mu_0 H \leq 0.8$ T, applied perpendicularly to the probed surface of the sample (i.e. parallel to the superconductor c -axis in c -axis oriented samples). The field-dependent cavity quality factor Q and resonant frequency ν are

measured to yield the corresponding surface impedance variations according to the following equations:

$$\begin{aligned}\Delta R_s(H, T) &= R_s(H, T) - R_s(0, T) = \\ &= G \left[\frac{1}{Q(H, T)} - \frac{1}{Q(0, T)} \right]\end{aligned}\tag{1}$$

$$\begin{aligned}\Delta X_s(H, T) &= X_s(H, T) - X_s(0, T) = \\ &= -2G \frac{\nu(H, T) - \nu(0, T)}{\nu(0, T)}\end{aligned}\tag{2}$$

where G is a geometric factor of the cavity which can be computed from the theoretically known distribution of the electromagnetic field. Here, $G \approx 10840$ and $G \approx 2000$, for the cavity and the dielectric resonator, respectively. Samples smaller than the base of the resonators are accommodated with the aid of an auxiliary thin metallic mask. In this case the geometric factor increases and sensitivity decreases.

Measurements are performed by quasi-statically sweeping the applied field intensity H at fixed temperature after zero field cooling. It is worth noting that by considering field-induced variations of Z_s , no calibration of the cavity response is needed since the latter is field independent.

As already anticipated in the previous Section, the in-field surface impedance is determined by two main contributions: grain boundaries and vortex motion.

Grain boundaries, depending on the misalignment angle between adjacent grains, exhibit behaviours ranging from metallic to Josephson tunneling. In magnetic fields, they constitute preferential paths for the motion of vortices, yielding generally lower pinning forces along their direction: the actual nature of the vortices located in the GB depends again on the misalignment angle. With larger and larger misalignment angle, the nature of vortices changes from standard Abrikosov vortices to the so-called Abrikosov-Josephson (AJ) vortices, and finally to core-less Josephson vortices

[13]. Many models have been developed in order to capture the GB behaviour in the microwave regimes [14–17]. Independently from the adopted model, the main signature of GB in the in-field microwave surface impedance consists in an abrupt, quasi-step-like increase of the surface resistance R_s with increasing field, followed by a flat plateau [14, 18]. The field scale over which the step actually extends varies from a few mT [14, 18] for weak-links and Josephson vortices up to 0.1 T or larger for AJ vortices [13, 19].

Abrikosov vortex motion within intragrain regions is the ubiquitous phenomenon visible in surface impedance measurements in the mixed state. The mixed state microwave response, which includes vortex dynamics, is quite intricate, since it emerges from the interplay between the currents excited by the applied microwave fields and vortices set in motion by these currents. Many authors considered this issue, providing models which take into accounts various aspects [20–24]. Following Coffey-Clem (CC) approach [21], the whole complex resistivity $\tilde{\rho}$ can be written down as follows:

$$\tilde{\rho} = \frac{\rho_{\text{vm}} + i\omega\mu_0\lambda^2}{1 + i\frac{2\lambda^2}{\delta_{\text{nf}}^2}} \quad (3)$$

where $\omega = 2\pi\nu$ is the microwave angular frequency, ρ_{vm} is the complex resistivity due to Abrikosov vortex motion, and λ and δ_{nf} are the London and normal fluid penetration depths, respectively.

Vortex dynamics involves many mechanisms: the interaction with the superconducting condensate yields a viscous drag, described through a viscous drag coefficient (also commonly called vortex viscosity) η . The interaction between crystal defects and the fluxon system generates a pinning effect usually described through the pinning constant k_p , applicable in the limit of small vortex displacements from their equilibrium positions as determined by high frequency stimuli. Thermal fluctuations

allow for thermally activated flux jumps between pinning sites, yielding the so-called creep.

One finds [25] that a large variety of different models can be formulated under the following very general expression for the vortex resistivity ρ_{vm} :

$$\rho_{\text{vm}} = \rho_{\text{ff}} \frac{\epsilon + i \frac{\omega}{\omega_0}}{1 + i \frac{\omega}{\omega_0}} \quad (4)$$

where $\rho_{\text{ff}} = \Phi_0 B / \eta$ is the flux flow resistivity, B the magnetic induction field, Φ_0 the flux quantum, ϵ a dimensionless creep factor, constrained in the range $[0,1]$. When creep can be neglected ($\epsilon = 0$), the above expression reverts to the well-known Gittleman-Roseblum model [20].

The relation (in the local limit) between the superconductor complex resistivity $\tilde{\rho}$ and the measured surface impedance depends on the penetration depth of the e.m. field with respect to the superconducting sample thickness d : for bulk samples, i.e. $d \ll \min(\lambda, \delta_n)$, one has:

$$Z_s(H, T) = \sqrt{i\omega\mu_0\tilde{\rho}} \quad (5)$$

whereas in thin films, for which the $d \gg \min(\lambda, \delta_n)$ condition holds, [26]:

$$Z_s(H, T) = \frac{\tilde{\rho}}{d} \quad (6)$$

3. Measurements and Discussion

3.1. DyBCO single domains

DyBCO single domains were prepared with precursor powders $\text{DyBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $\text{Dy}_2\text{BaCuO}_5$, produced by solid-state synthesis from Dy_2O_3 , BaCO_3 and CuO powders. The powder mixture was pressed uni-axially to give cylindrical pellets of 10.8 mm diameter, which were melt-textured in atmospheric air conditions using

a Nd-123 single-crystal seed. Large “quasi-single-crystals”, mainly c -axis oriented, have been obtained, with $T_c \sim 88$ -89 K. Two distinct pellets, (A) and (B), having similar $T_c \approx 88$ K, will be considered in the following.

From the first pellet (A), two samples of about the same thickness ~ 1 mm were cut: one (A2), approximately 2×2 mm² square, has been characterized by a magneto-optic (MO) study.

Magneto-optic images are reported in Fig. 1 (bright regions denote higher field intensity, black regions denote zero field): a static magnetic field is applied, perpendicularly to the sample surface, after a ZFC of the sample down to 73.5 K. In panel (a) the field is set to 15 μ T: the sample is not threaded by magnetic flux, thus exhibiting a single domain behaviour. At higher field values (90 μ T, panel (b)), the magnetic flux penetrates in the sample: a few cracks, along which flux lines preferentially enter the sample are visible. Going back to zero field (panel (c)), remnant flux (indicative of significant pinning) is visible with slight dishomogeneities, apart from the cracks, along which flux lines easily exit from the sample volume. Through the MO analysis the sample shows an overall single domain behaviour, with no visible microscale flux penetration.

The parent sample (A1) is a ~ 10.2 mm side square and is used for the microwave measurements [27] performed by means of the cavity operating at 48.3 GHz. Measurements of $\Delta R_s(H)$ and $\Delta X_s(H)$ at selected temperatures are reported in Fig. 2. It can be seen that the surface resistance increases with the field, with steeper increase at larger T . At low fields there is no evidence for step-like increase of the dissipation: we deduce that no significant contribution to the losses comes from weak-links or Josephson fluxons. The absence of signatures of JJ or AJ vortices confirms the MO: the sample does not present significant grain boundaries, thus

behaving as a single domain also at microwaves.

On the other hand, the surface reactance is featureless and essentially flat, remaining within the same error range ($\pm 0.01 \Omega$, denoted by the thick horizontal lines) for the temperature range here presented. Despite large scattering than in R_s data, due to the sensitivity limits of the cavity used for the measurements, $\Delta X_s(H)$ clearly remains well below ΔR_s and constant with H : this is a clear indication of irrelevance of pinning at our measuring frequency. In fact, one can see that the primary effect of pinning is an increase of the reactance (connected to the elastic forces recalling vortices to the pinning centers). Analytically, it can be seen by inserting Eq. (4) in Eq. (5), and taking limits for small fields and large pinning, that $\Delta X_s/\Delta R_s \sim k_p/(\eta\omega)$. Since we find that $\Delta X_s(H)$ is negligible with respect to $\Delta R_s(H)$, we can safely neglect pinning in the analysis of our data.

It is worth stressing that undetectable pinning in the high frequency regime does not necessarily imply small pinning in the d.c. transport regime: high frequencies force flux lines to undergo to very small oscillations (small displacement regime), thus probing mainly the steepness of the pinning wells. By contrast, low frequencies and dc force flux lines to large displacements, thus probing mainly the pinning barrier heights. Indeed, similar DyBCO samples were found to present significant pinning through d.c. and magnetic characterizations [31]. The same presence of remnant magnetization, as seen with MO, points to a significant pinning in the quasistatic regime.

By neglecting pinning effects (therefore neglecting also creep), and by considering that, not too close to T_c , the London penetration depth is much shorter than the normal fluid penetration depth, Eq. 3 reverts to $\tilde{\rho} \approx \rho_{vm} + i\omega\mu_0\lambda^2$ with $\rho_{vm} = \Phi_0 B/\eta$,

which allows to compute the surface resistance in the bulk limit as:

$$\Delta R_s(B, T) = \frac{\omega \mu_0 \lambda}{\sqrt{2}} \sqrt{-1 + \sqrt{1 + \left(\frac{1}{\omega \mu_0 \lambda^2} \frac{\Phi_0 B}{\eta} \right)^2}} \quad (7)$$

The theoretical expression Eq. (7) predicts a crossover from the linear behaviour at low fields,

$$\Delta R_s = \frac{1}{\lambda} \frac{\Phi_0 B}{\eta}, \quad (8)$$

when the material has a (real) flux flow resistivity $\rho_{\text{ff}} = \frac{\Phi_0 B}{\eta}$ and screening is dictated by superfluid over the London penetration depth λ , to a square-root dependence at higher fields. The crossover is ruled by a threshold field value proportional to $\lambda^2 \eta$. In the general case, Eq. (7) yields a downward curvature on $\Delta R_s(H)$, which allows to fit well the experimental data. Within the London limit $B \simeq \mu_0 H$, and fits of the experimental curves $\Delta R_s(H)$ can be performed. Full fits, together with the fitting parameters λ and η , have been reported elsewhere [27]. Sample fits are reported in Fig. 2. In the following Section 4, we will discuss the viscosity values derived from fits of the data with Eq. 7.

The second sample (B1) cut from pellet (B) presents additional features. Surface resistance data for selected temperatures are shown in Fig. 3. It can be seen that $\Delta R_s(H)$ increases at a quicker rate than in sample A1: given their similar T_c , this implies that sample B1 is more dissipative¹. Moreover, an initial step is visible at moderately low fields (up to ≈ 0.1 T), after which ΔR_s increases linearly with the field, in contrast with the downward curvature seen on sample A1. The initial step is, as already anticipated, typical of grain boundaries, and the linear increase of ΔR_s

¹This fact also contributes to limiting the system sensitivity so that surface reactance can not be determined.

is due to standard Abrikosov vortex dynamics. A prototypical measure of this kind of behaviour is shown by data taken on granular samples, like the data for ΔR_s at 23 GHz of a $\text{GdBa}_2\text{Cu}_3\text{O}_{7-\delta}$ granular sample [29] reported in the inset of Fig. 3. Fits of the linear part of the data in Fig. 3 yield the product $\lambda\eta$ vs. T as fit parameter. We find that $\lambda\eta$ is approximately the same in the two samples, as reported in Fig. 3, panel (b). However, in sample B1 $\Delta R_s \propto B$, whereas in sample A1 ΔR_s has a downward curvature. This fact implies that (a) λ in sample B1 is larger than in A1, indicating a larger penetration of the microwave field and that (b) η is smaller.

An estimate of λ and η can be given as follows. The product $\lambda\eta$ is fixed by the fits of data with Eq. (8): λ is then increased until the calculated curve by Eq. (7) coincides with the data. This procedure yields $\lambda_{(\text{sampleB1})} \geq 3.5\lambda_{(\text{sampleA1})}$, and $\eta_{(\text{sampleB1})} \leq 3.5\eta_{(\text{sampleA1})}$. A larger λ implies a larger disomogeneity in the sample, coherent with the stronger signature of GB observed; the simultaneous reduction of η will be discussed below.

3.2. YBCO thin films with artificially enhanced pinning

In the previous Subsection we have presented microwave measurements on DyBCO single domain samples, detecting no pinning (at least, no significant pinning visible in this high frequency dynamic regime), which allowed us to extract the vortex viscosity, a physical quantity connected with intrinsic properties of the material. In this Subsection we briefly present data taken on YBCO epitaxial thin films, where nanosize BaZrO_3 (BZO) particles were intentionally added in order to artificially improve the pinning properties. These systems qualify themselves as strongly “extrinsic” with respect to the DyBCO monodomain. The YBCO/BZO thin (thickness $d \approx 120$ nm, $T_c = 90$ K) film here considered was grown by pulsed

laser ablation from a target with 7 mol.% BZO content. BZO particles are typically extended (correlated) defects, of transverse size of a few nm [28]. Measurements were performed with the dielectric resonator at 47.7 GHz. A typical measurement at 63 K is reported in Fig. 4. It is worth to stress that a large surface reactance is observed, pointing to a very strong pinning in this sample: for the measurement shown, $\Delta X_s(H) > \Delta R_s(H)$. Data analysis is straightforward: no initial steps are detected, indicating good connectivity of the film. Given the thickness of the film, Eq. 6 holds; since $T \ll T_c$, $\lambda \ll \delta_n$ and creep can be safely considered negligible, so that Eqs. (3) and (4) yield $\tilde{\rho} = \rho_{ff} \frac{1}{1 - i\nu_p/\nu} + i\omega\mu_0\lambda^2$. Finally, by considering only the field-induced variations and neglecting any pair-breaking effects on λ since $B \ll B_{c2}$, one has in the London limit $\Delta Z_s(B \approx \mu_0 H) = \frac{\rho_{ff}}{d} \frac{1}{1 - i\nu_p/\nu}$. Therefore the quantities η and $k_p = 2\pi\nu_p/\eta$ can be directly derived from $\Delta R_s(H)$ and $\Delta X_s(H)$, without the need of any fitting procedure. A detailed study of the possible effect of creep has been reported in [25]. Extended reports on YBCO/BZO have been published elsewhere [10, 32]. We are here concerned specifically with the values of the vortex viscosity, in order to compare such intrinsic quantities in different RE-BCO systems.

4. Comparison of vortex viscosities

We now comment and draw some conclusions about the vortex viscosities as extracted through mixed state microwave measurements performed on various materials and samples. In Fig. 5, viscosities of various 123 systems are shown: namely, the DyBCO monodomain measured at 48.3 GHz, the YBCO/BZO thin film measured at 47.7 GHz, and a YBCO single crystal measured at 40.8 GHz (from Ref. [9]).

From Fig. 5, it can be seen that all the considered samples exhibit viscosities with

similar absolute values and temperature dependencies. Since η is determined by the quasi-particles scattering times and density of states in the vortex cores (together with a contribution arising from the regions around the vortices, given the d-wave nature of HTCS [30]), this fact allows to infer that all these 123 systems, despite their structural and “extrinsic” differences, share the same fundamental physics of quasiparticles in the mixed state. This is contrasted by the measurements taken in DyBCO sample B1, where we estimate a vortex viscosity smaller by a factor ~ 3.5 (continuous line in Fig. 5).

The latter observation deserves a specific comment. In fact, an explanation can be given as follows: since $\eta \propto n\tau$ (being n and τ the quasi-particles concentration and scattering time, respectively) [7], it comes out that sample B1 is affected by a significant disorder on the nanoscale (appreciable on scales of the order of the vortex size). The simultaneous appearance of disorder on microscale, as indicated by the appearance of weak-links fingerprints (see Fig. 3 and the discussion of the weak-links induced microwave losses in Ref. [14]), is an intriguing coincidence that will be further studied in future experiments.

5. Conclusions

We have presented and compared mixed state microwave measurements performed on various HTS RE-BCO system, including DyBCO monodomains and YBCO epitaxial thin films with artificially introduced nanoparticles. We have shown that the microwave techniques gives important information, complementary to dc investigation. In particular, it is possible to obtain the intrinsic vortex viscosity even in very strongly pinned materials. We have extensively characterized DyBCO monodomains, and we have found that they can exhibit the same microwave viscos-

ity than YBCO crystals and thin films with artificially included nanoparticles, thus indicating the same quasiparticle physics. We have also shown that DyBCO monodomains in some case can exhibit simultaneous microscale inhomogeneity, leading to weak-links, and possible nanoscale inhomogeneity, leading to a small scattering time as revealed by smaller viscosity.

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Figure 1: MO images of DyBCO sample A1, taken at 73.5 K after zero-field cooling, by applying a magnetic field equal to 15 μT (upper panel), 90 μT (middle panel) and going to zero again (lower panel). Bright regions denote higher field intensity, black regions denote zero field.

Figure 2: Field-induced variations of the surface impedance of DyBCO sample A1 at 70 K and 84 K, upper panel and lower panel, respectively. Continuous lines are fit of ΔR_s according to Eq. 7.

Figure 3: Upper panel: $\lambda\eta$ products for DyBCO samples A1 e B1 (bicolor and crossed squares, respectively). Lower panel: field-induced variations of the surface resistance of DyBCO sample B1 at selected temperatures. The straight lines are guides for the eye. Inset of lower panel: data at 23 GHz of a $\text{GdBa}_2\text{Cu}_3\text{O}_{7-\delta}$ granular sample [29].

Figure 4: Field-induced variations of the surface impedance of YBCO/BZO thin film at 63 K.

Figure 5: Vortex viscosity vs T/T_c for a set of 123 materials measured at similar frequencies: DyBCO single domain (sample A1), full dots; YBCO/BZO thin film [10], open circles; YBCO single crystal [9], squares. The continuous line is the estimated value for DyBCO sample B1.

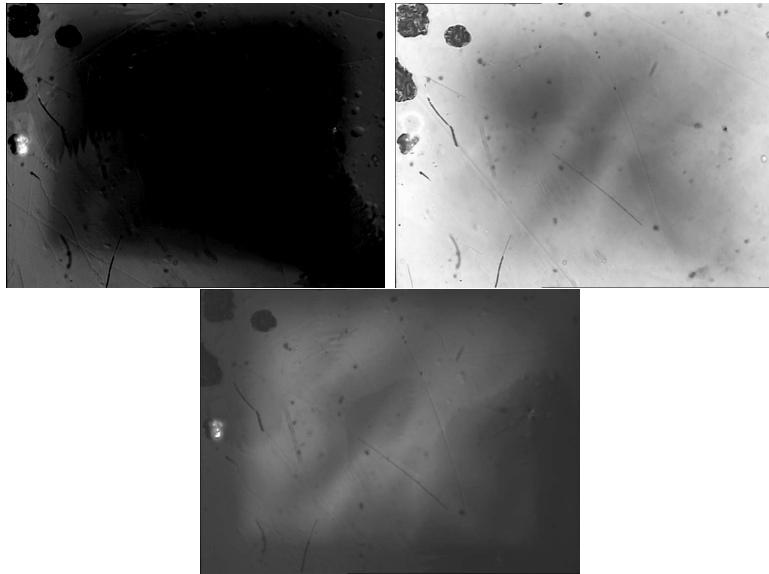


Figure 1

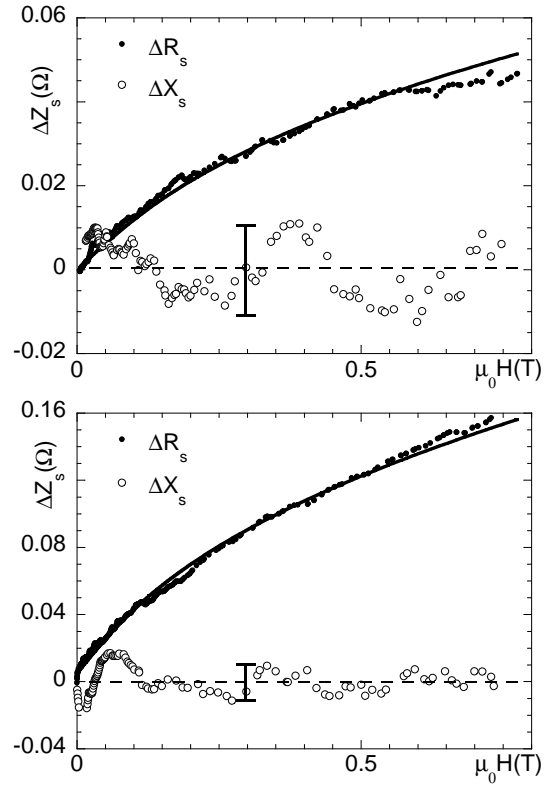


Figure 2

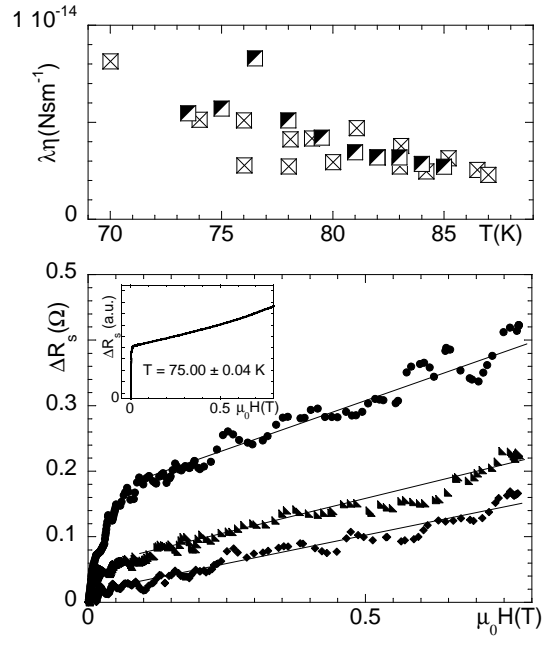


Figure 3

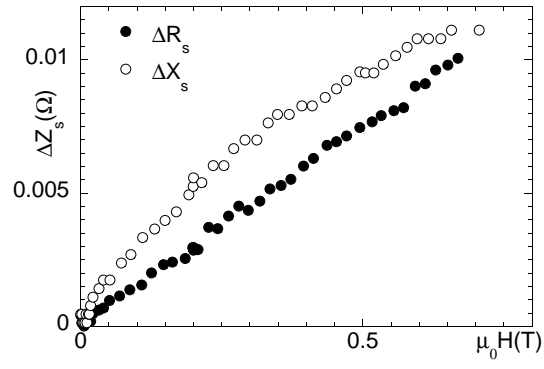


Figure 4

